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SIMULATION AND MODELING OF FUEL INJECTION SYSTEM OF A DIESEL ENGINE

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ABSTRACT
In order to achieve best brake specific fuel consumption and reduced emissions in a diesel engine the fuel injection system of a diesel engine has to be understood. The fuel injection parameters are very important in controlling the combustion and emission mechanism. In this work a fuel injection system is simulated for prediction of the performance of the combustion process. Using the basic continuity equation for the plunger chamber, delivery chamber and the nozzle chamber a mathematical model is developed. Equations of motion for the delivery valve and nozzle needle are obtained using Newton's second law of motion. Using simulink package of the MATLAB software, subsystems are created and connected. Simulated quantities are the plunger chamber pressure, delivery chamber pressure and nozzle chamber pressure. This simulation can be an effective tool for predicting the performance of a fuel injection system for further research and development.

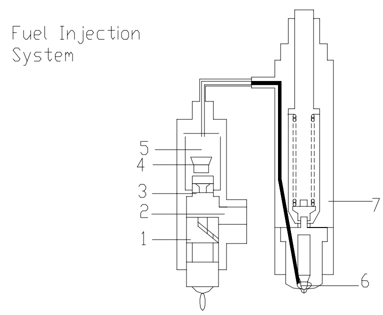
1. INTRODUCTION
Diesel engines are popular due to relative simplicity, high power density and high efficiency capabilities. However the traditional engine suffers from relatively high Nitrogen Oxide (NOx) and particulate emissions. Therefore the research on engines is mainly focussed on emissions reduction. A thorough understanding of diesel combustion will enhance the effectiveness of the current methods and strategies and may provide insight into possibilities of new improvements.

The combustion process is dependant on the fuel injection parameters. Precise control over the fuel injection is necessary to control the combustion process. Instead of extensive and expensive prototype testing in fuel injection system, which is also time consuming, mathematical models and simulation can be created. This enables one to understand the system behavior evaluation of various design or operational strategies. Due to the complicated nature of the fuel injection system and the number of components involved like fuel pump, delivery valve injector needle valve etc, it is difficult to reach the optimum solution by trial and error methods. An accurate method to solve the problem of simulating the operation of fuel injection system is to model each sub system and then to connect them as a system.

Vilmar Aesoy *etal* (1) have developed fuel injection system model using the Bond graph theory. Instead of complex set of mathematical equations a fundamental graphical structure of the bond graph was developed and analyzed. In order to reduce the diesel emissions Hirofumi Imanishy *etal* (2) have simulated the effects of Injection rate. The controlling of injection rate has a potential for simultaneous reduction of smoke and NO_x. In industry high injection pressures are used with small hole nozzles for particulate reduction strategy.

In this work modeling is done for the fuel injection system using simulink software. . This model is almost similar to the model developed by Paquari Valavane and is capable of predicting the pressure variation at various points of injection system. It consumes only a few seconds to simulate. It is easy to change the geometrical parameters without any difficulty.

2. FUEL INJECTION SYSTEM
The common arrangement for fuel injection system in diesel engine uses a plunger in barrel pump connected by a fuel line to a fuel injector.



1. Plunger. 2. Intake port 3. Plunger chamber.4. Delivery valve 5. Delivery chamber
6. Nozzle head

For modeling, the injection system is divided into three parts namely pump, injection pipe and nozzle side. The events are further divided as below for convenience.

2.1 Pump side

1. Plunger moves up but the pressure is not sufficient in the plunger chamber to lift the delivery valve.
2. Delivery valve begins to move
3. Residual pressure is propagating in the injection pipe.

2.2 Nozzle side

1. Pressure wave is reflected to the pump side since the pressure in the nozzle chamber does not exceed the opening pressure of the needle valve
2. Needle valve opens and fuel is injected
3. Needle valve reaches the maximum lift and this state continues for some time until the pressure drops.
4. The needle valve closes

At high speeds the injection time reduces and the injection pressures will be greater. For accurate fuel metering, leakage from the pump element has to be minimum. The leakage is directly proportional to the fuel density, pressure difference, reciprocal of viscosity and cylinder barrel clearance. In order to prevent leakage the barrel and the piston are lapped to a clearance of one micrometer.

The fuel injection pump has a camshaft that gets the drive from the engine at half the speed of the engine. The cam actuates a piston which ensures pressurization of the fuel. The fuel flow rate delivered by the pump is a function of the rotary speed and angular orientation of the pump piston.

The volume injected by the pump partly depends on this section of passage between the compression chamber and filling source.

Table: 1 The profile of the cam and plunger lift.(4)

Angle of the cam	Plunger lift
30	.5
60	1.3
90	3.0
120	6.9
150	9.7
180	10.0
210	9.2
240	6.8
270	4.0
300	2.0
330	0.85
360	0.45

2.3 Assumptions

When forming equations of continuity and valve motion the following assumptions are made:

1. Temperature change due to pressure and time during cycle is not considered.
2. The value of bulk modulus of fuel oil and sound velocity are selected so as to correspond to residual pressure in the pipe line. The viscosity, density, and sound velocity are assumed to be constant throughout the cycle.
3. The vapour pressure of the fuel is small compared to the level of the pressure injection system and therefore it is assumed that cavitations will occur when the pressure drops below 0 kg/cm^2.
4. It is assumed that at any instant the pressure is uniform in each chamber and in each divided section of the injection pipe.
5. The steady state value of 0.63 is employed for discharge coefficient at the orifice and the nozzle hole.
6. Elastic deformation in the injection system is not considered.

The analytical model which is programmed for a time variant simulation on the MATLAB software , includes accurate description of the geometric and physical character of the system, as well as the equations that describe the dynamics of the fluid and mechanical components.

3. EQUATIONS FOR SUBSYSTEMS

Continuity equations for each volume are represented by,

3.1. Pump side

3.1.1 The equation for continuity in the plunger chamber.

The plunger displacement= the compressibility within the plunger chamber + out flow through the delivery chamber + the change in volume due to the delivery valve motion

$$U_p A_p = \frac{V_p}{E_p}\frac{dp_p}{dt} + \otimes C_{pA} A_{pA}\sqrt{\frac{2g}{\rho}}(P_p - P_{ps})$$

$$+ \otimes C_{pb} A_{pb}\sqrt{\frac{2g}{\rho}}(P_p - P_{ps}) + A_d\left[\frac{dy_d}{dt}\right]$$

$$+ \otimes C_{da} A_{da}\sqrt{\frac{2g}{\rho}}\left(P_p - P_d\right)$$

3.1.2.Equation of continuity in the delivery chamber

Flow to the delivery chamber = change in volume caused by the motion of the delivery valve + compressibility in the delivery chamber+ flow into the injection pipe.

$$S_d \frac{dy_d}{dt} + C_{pa} A_{pa}\sqrt{\frac{2g}{\rho}}\left(P_p - P_d\right)$$

$$= \frac{V_d}{E_d}\frac{dP_d}{dt} + U_{LS} S_l$$

3.1.3 Equation of motion of the delivery valve

When W_{do} is the sum of the force of the residual pressure and the spring force, the equation of the delivery valve motion is given by,

$$M_d\left(\frac{d^2y}{dt}\right)+C_d\frac{dy_d}{dt}+K_dY_d$$
$$=C_{da}\left(P_p-P_d\right)-W_{do}$$

3.1.4. Boundary condition in the pipe end

The pressure loss in the injection pipe end cannot be ignored. When the pipe pressure at the entrance is P_{L1} the boundary condition becomes as follows:

$$P_d = P_{in} + c\frac{\rho}{2g}U_{LS}^2$$

where C is the coefficient of pressure loss at the delivery chamber exit.

3.1.5.Lift of the plunger

This polynomial expression represents lift as a function of time. This is for 1000 rpm for the cam shaft speed. This equation was fitted with the plunger data as given in the table: 1

$$Y = p1\times t^8 + p2\times t^7 + p3\times t^6 + p4\times t^5$$
$$+ p5\times t^4 + p6\times t^3 + p7\times t^2 + p8\times t^1 + p9$$

where p1, p2… are constants having the values as follows.

p1 = 4.726e+12;
p2 = -5.241e+11;
p3 = -4.570e+10;
p4 = 9.9514e+10;
p5 = -5.849e+09;
p6 = 1.4225e+08;
p7 = -1.238e+07;
p8 = 363.7;
p9 = 0.43572;

3.1.6. Equation for plunger velocity

By differentiating the above equation the equation for plunger velocity is obtained.

$$U_p = 8p1\times t^7 + 7p2\times t^6 + 6p3\times t^5 + 5p4\times t^4$$
$$+4p5\times t^3 + 3p6\times t^2 + 2p7\times t^1 + p8$$

3.2 Equations for nozzle side

3.2.1 Continuity equation in the nozzle chamber

The amount of fuel entering into the nozzle chamber from the injection pipe is equal to the sum of the compressibility in the nozzle chamber, the volume change due to nozzle motion and the leakage between he needle and the barrel

$$U_{LL}S_i = \frac{V_n}{E_n}\frac{dP_n}{dt} + S_{na}\frac{dY_n}{dt}$$
$$+ \otimes C_{nc}A_{nc}\sqrt{\frac{2g}{\rho}}\left(P_n - P_{cyl}\right)$$

3.2.2 Equation of needle valve motion

The equation of valve motion is given by ,

$$M_n\left(\frac{d^2y_n}{dt}\right)+C_n\frac{dy_n}{dt}+K_nY_n$$
$$=C_{nsa}\left(A_{na}-A_{nb}\right)+\left[S_{na}-C_{nsa}\left(A_{na}-A_{nb}\right)\right]P_{cyl}$$
$$-\left(A_{na}P_{air}\right)-\left(W_{no}\right)$$

3.2.3 Boundary condition of pipe end

Since the pressure loss at the pipe end could be ignored due to the divergence at the pipe end , the pressure of pipe end (P_j) is equal to the nozzle chamber pressure. Therefore the following equation is obtained.

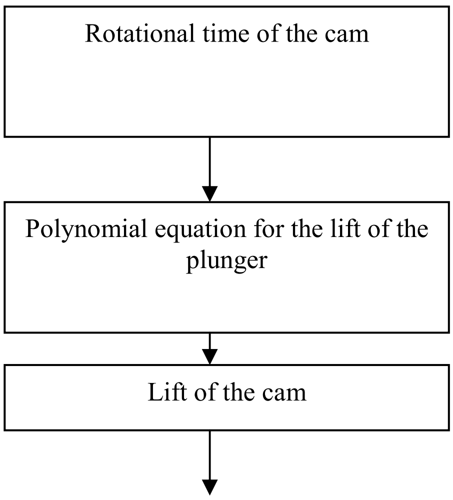
$$P_j = P_n$$

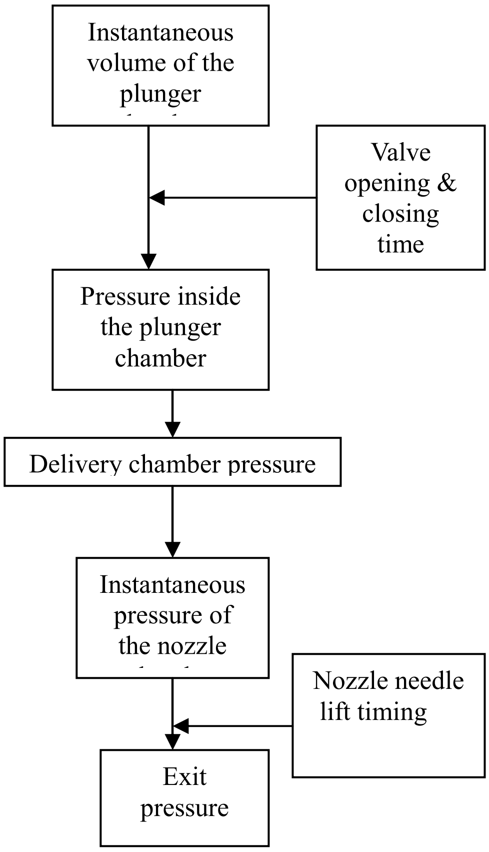
3.2.4 Working of the simulation model

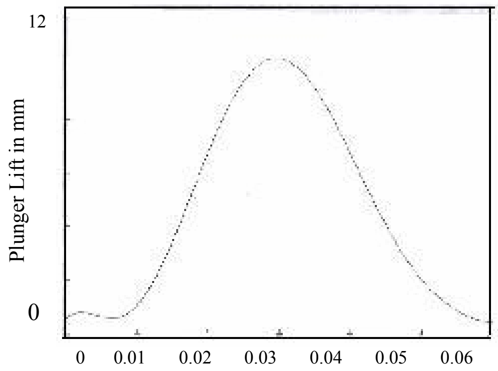
For modeling, simulink provides graphical user interface for building models as block diagrams. The fuel injection system can be represented as a set of interconnected subsystems like plunger chamber, delivery chamber and nozzle chamber. Based on the respective governing equation each subsystem is constructed.

After modeling the subsystems of plunger chamber, delivery chamber and the nozzle chamber they are connected to form an over all model. Provisions are also made to monitor pressure at various points.

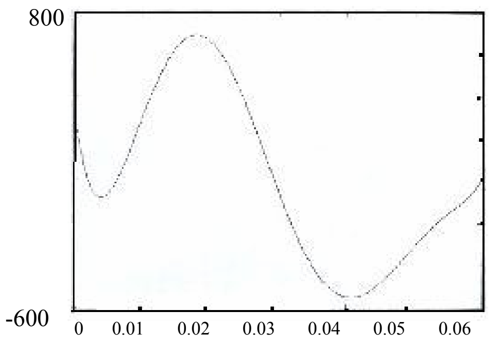
The flow chart explains the working of the model. The timings are calculated for the four stroke diesel engine at a speed of 2000rpm for which the cam shaft speed is speed is 1000 rpm.



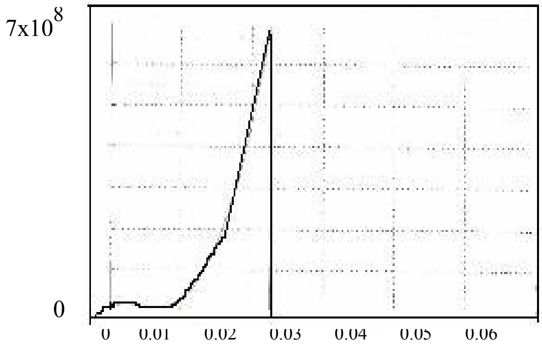




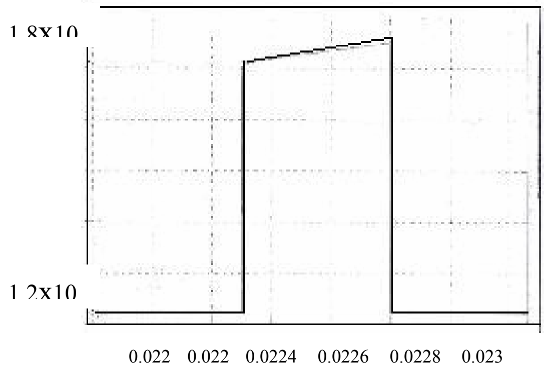
Time in seconds
Fig-1 Plunger Lift in mm



Time in seconds
Fig-2 Plunger Velocity in mm/s



Time in seconds
Fig-3 Plunger Chamber pressure in Kg/m^2



Time in seconds
Fig-4 Delivery Chamber pressure in Kg/m^2

4. RESULTS AND DISCUSSIONS

Plunger lift was obtained from the simulation as it is seen in figure (1). The maximum lift is reached at .03 seconds. This is the result of the polynomial equation .The differentiation of the plunger lift is the velocity. This curve is in the form of a sinusoidal wave form. The higher starting value is due to the residual error in the polynomial equation. The maximum velocity of plunger is around 700 mm/sec and is reached at .02 seconds. The plunger pressure as seen from the figure (3) increases gradually till the delivery valve opens at .025 sec. Then the pressure suddenly decreases due to opening of the needle valve. This resembles a pulse. The delivery chamber has an initial pressure which is maintained till the opening of the delivery valve when the pressure suddenly increases till nozzle needle valve opens. This is observed from the figure (4). The pressure variation is very steep and the time of injection also could be obtained from this modeling. The reason for the very high pressure in this simulation is due to maintaining the volume chamber as constant throughout the simulation time.

5. CONCLUSION

A simulation of the mathematical model is proposed in which the pressures at various points like plunger chamber and delivery chamber can be predicted. Many system models do not have easy ways to assess the effects on their mode, or by removing of elements. This model is created using the subsystems, which are then assembled into an overall model, which is very useful in altering the parameter to see its effects on the injection pressures. Modifications are easy to make by adding new elements to the system model. It is proposed to conduct experiments to validate this model. The results reported indicate that the fuel injection system can be simulated with MATLAB reducing much of the mathematical calculations and techniques.

6. REFERENCES

1. Vilmar Aesoy,Hallvard Engia and Leif Arne Skaboe. “Fuel Injection system design, analysis and testing using bond graph as an efficient modeling tool”SAE Paper962061
2. Hirofumi Imanishi, Takuo Yoshizaki, and Hiroyuki Hiroyasu. “Simulation study of effects of injection rate profile and air entrainment characteristics on D.I. diesel combustions Paper 962060
3. M.Paquari Valavane(2003). “ Development of simulation model for fuel Injection System.”M.E. Thesis, Regional Engineering College,Trichy.
4. E.Benjamin Wylie, Jay A. Bolt, and Mohamed F. EI- Erian (1991) “Diesel fuel injection system simulation and experimental correlation”.
5. D.A. Kouremenos, D.T. Hountalas and A.D. Kouremenos “Development and validation of a detailed fuel injection system simulation model for diesel engines.” SAE Paper-1999-01-0527

7. NOMENCLATURE AND SUBSCRIPTS

Subscripts	**Meaning**
p	Plunger chamber/plungerd
d	Delivery valve/delivery chamber
I	Injection pipe
n	Nozzle chamberp
a	Fuel supply port
pb	Spill port
da	Connecting port
na,nb	Nozzle needle valve
nc	Nozzle hole
de	Thrust coefficient of delivery valve
nsa	Thrust coefficient of needle valve
LS	Exit of delivery chamber
LL	Entrance of nozzle chamber

Symbol	Meaning	Unit
Γ	Specific weight of fuel oil,	kg/m^3
P	Density of fuel	kg/ m^3
G	Acceleration due to gravity	m/s
E	Bulkmodules of the fuel	kg/m^2
A	Sound velocity of fuel	m/s
T	Time	s
V	Volume,	m^3
P	Pressure	kgf / m^2
U	Velocity	m/s
Y	Lift ,	m
A,S	Area ,	m^2
M	Equivalent mass	$kg\ s^2/m$
C	Damping factor	kg s/m
K	Spring constant	kg / m
M	Discharge coefficient	dimensionless